Climate Models & Climate Sensitivity

Paul Kushner
Department of Physics,
University of Toronto
Infrared light $h\nu \sim 0.3 \text{ eV} \sim 7 \times 10^{-29} \text{ LHC}$

Infrared flux $\sim 240 \text{ W/m}^2 \sim 0.3 \mu \text{LHC/(m}^2 \text{ s)}$

Total infrared radiance $\sim 10^{11} \text{ MW} \sim 200 \text{ MLHC/s}$

Bony et al. 2006
Infrared Cloud Image

Extratropical Macroturbulence: Baroclinic eddies

Tropical Macroturbulence: Convective systems

Bony et al. 2006
Extratropical Macroturbulence

5-day centered 500 MB Heights/Anomalies (dekameters) valid 00Z 01 Dec 2007

Univ. of Washington Dept. of Atm. Sci.

Mike Wallace
Tropical Macroturbulence

Mike Wallace
GCMs match observed trend and interannual variations of tropical mean (ocean only) column water vapor when given the observed ocean temperatures as boundary condition.

Courtesy of Brian Soden & Isaac Held

Bony et al. 2006
Climate Sensitivity in Climate Models

Bony et al. 2006
Climate Sensitivity in Climate Models

Uncertainty in gain factors normally distributed. But uncertainty in climate sensitivity is right skewed.

Finite probability of large climate change from remaining feedbacks (e.g. biospheric --- Torn and Harte)

Roe & Baker 2007
Climate Models and Climate Sensitivity,

Earth System Schematic

Physics of Climate Change Program @ KITP ’08

Context: Key quantity of interest: “climate sensitivity”

\[ \left( \frac{\partial T_s}{\partial \log_2[CO_2]} \right)_R, \]

\[ CO_2: \log_2[CO_2], T_s \text{ surface temperature, } R = 0 \text{ radiative equilibrium.} \]

Program themes:

1. “Macroturbulence”
2. “Clouds”
3. “Ecology”

Tools for cross-talk:

1. Global observing system & data
2. Quantitative numerical models
3. Theory

Simple Climate Model

Long squiggle

\[ L, \lambda \sim 4 \mu m \]

Net shortwave, TOA

Net longwave, TOA

Short squiggle

\[ S, \lambda \sim 600 \text{ nm} \]

SUN

EARTH
Radiative equilibrium, blackbody: $S=L=\sigma T_e^4 \sim 240 \text{ W/m}^2$

Emission temperature: $T_e=T(Z=Z_e) \sim 255 \text{ K}$

Emission height: $Z_e \sim 5 \text{ km}$.

Surface temperature: $T_s=T(Z=0) \sim 288 \text{ K} > T_e$ --- greenhouse effect (Fourier)

\[ \Gamma = -\frac{dT}{dZ} \]

$\Gamma_{rad}=a\tau/(\tau+b)$, $a$&$b$ positive.
$\tau$: optical thickness from main GHGs -- H2O, CO2

$\Gamma > \Gamma_c = g/c_p$: atmosphere is convectively unstable.

**Macroturbulence & climate questions:**
What sets $T_s=T_s(x,y,z)$?
What sets $\Gamma=-dT/dz$ (stratification)?

How will climate change affect $T_s$ and $\Gamma$? Radiation, fluid dynamics, water vapor, clouds.

**Macroturbulence regimes:**

\[ Ro = \frac{T_{adv}}{2\Omega \cdot \hat{r}} = \frac{U}{\Omega L} \ll 1 \]

$\delta = H/L \ll 1$

$\frac{N^2}{f^2} \delta^2 \sim 1$

$Ro \sim 1, \delta \sim 1$
Extratropical regime:
Well simulated by models

Theory:
“Weather”: dry, quasi-horizontal, non-­divergent
“baroclinic turbulence” and teleconnections (ENSO, NAO, annular modes): linear and nonlinear.
Eddies transport heat poleward, maintain jets, maintain $\Gamma$.
Jets arise from $\beta = df/dy$
Clouds and moisture passive.

Tropical regime:
Not so well simulated
Clouds and moisture active.
Highly divergent; 3-D but coherent, not fully turbulent. Convective ascent + radiative descent maintains $T$.

Model-based Climate Feedback Analysis:
E.g. in our simple climate model
Double CO2, keep $\Gamma$, S fixed. “ceteris paribus”

Does emission temperature $T_e$ change? No! Instead, $Z_e$ increases.

$\Delta Z_e \sim 100$ m per CO2 doubling.

Radiative equilibrium: $R = L - S = R(T_s, \Gamma, CO2, H2O, C, I, V \ldots) = 0$[explain symbols]

- $CO2 \rightarrow CO2 + \delta CO2, T_s \rightarrow T_s + \delta T_s$, Everything else, “E” fixed
- $\delta R = R(T_s + \delta T_s, CO2 + \delta CO2, E) - R(T_s, CO2, E) \approx \left( \frac{\partial R}{\partial T_s} \right)_{CO2,E} \delta T_s + \left( \frac{\partial R}{\partial CO2} \right)_{T_s,E} \delta CO2 = 0$
- $\delta T_s = -\left( \frac{\partial R}{\partial T_s} \right)_{CO2,E} \delta CO2 = \left( \frac{\partial T_s}{\partial CO2} \right)_{R,E} \delta CO2$
- Radiative transfer: $\frac{\partial R}{\partial CO2} = -4W/m^2$.
- $\sigma T^4$: $\frac{\partial R}{\partial T_s} = 4W/m^2\cdot K$.
- So $\left( \frac{\partial T_s}{\partial CO2} \right)_{R,E} = 1K = \Delta_0$ “climate sensitivity”, no feedbacks

**Direct Feedbacks: Water Vapor, Clouds …**

“Feedback”: quantity affected by $\delta T_s$ and this affects $R$.

Direct: water vapor $H2O = e(T_s)$, $de/dT_s > 0$, $\partial R/\partial H20|_{T_s} < 0$. For variation in $T_s$,

$H2O(T_s) \rightarrow H2O(T_s) + \delta H2O(T_s) \approx H2O(T_s) + e'(T_s)\delta T_s$

Climate sensitivity with water vapor feedback.
\[
\left( \frac{\partial T_s}{\partial CO2} \right)_{R,E}^{H20} = \frac{\Delta_0}{1 - g_{H20}} \\
\text{gain: } g_{H20} = -\frac{\left( \frac{\partial R}{\partial H20} \right)_{CO2,Ts,E} e'(T_s)}{\left( \frac{\partial R}{\partial Ts} \right)_{CO2,H20,E}}
\]

-ve feedback \( g_{H20} < 0 \)
No feedback \( g_{H20} = 0 \)
+ve feedback \( g_{H20} > 0 \)

Runaway greenhouse \( g_{H20} \geq 1 \)
Current estimate \( g_{H20} \sim 0.4 \)

\[
\left( \frac{\partial T_s}{\partial CO2} \right)_{R,E}^{H20} = \frac{\Delta_0}{1 - g_{H20}} \sim 1.7K
\]

\( \left( \frac{\partial R}{\partial H20} \right)_{CO2,Ts,E} < 0. \) Radiative transfer model calculation: Critical region: tropical free troposphere (clouds).

\( e'(T_s) > 0. \) Climate model calculations: Transport, clouds.

Water vapor feedback: robust, well simulated for climate variations (volcanoes, El Niño).

**Climate sensitivity with cloud feedback:**

Gains are additive.

\[
\left( \frac{\partial T_s}{\partial CO2} \right)_{R,E}^{H20,C} = \frac{\Delta_0}{1 - g_{H20} - g_C}
\]

- Cloud feedback gain: \( g_C = -\frac{\partial R}{\partial C} \frac{\partial C}{\partial T_s} \frac{\partial T_s}{\partial R} \)
- \( \frac{\partial R}{\partial C} \) +ve for high clouds and -ve for low clouds.
- \( \frac{\partial C}{\partial T_s} \) is model dependent.
- \( g_C \) model dependent and controlled by low clouds (Pierrehumbert talk).

**Biospheric feedbacks (e.g. indirect on CO2)**

\( R = R(T_s, CO2) \) is independent of V but V depends on CO2.

Model for vegetation: \( V=f(CO2, T), (\partial f/\partial CO2)|_T<0, (\partial f/\partial T)_{CO2}>0?0? \)
Model for CO2, given emissions A and vegetation V: $\text{CO2} = \text{CO2}(A, V)$, $(\partial \text{CO2}/\partial A)_V > 0$, $(\partial \text{CO2}/\partial V)_A < 0$

- $\delta \text{CO2} = \left( \frac{\partial \text{CO2}}{\partial A} \right)_V \delta A + \left( \frac{\partial \text{CO2}}{\partial V} \right)_A \delta V$
- $\delta V = \left( \frac{\partial f}{\partial \text{CO2}} \right)_T \delta \text{CO2} + \left( \frac{\partial f}{\partial T} \right)_{\text{CO2}} \delta T$

$\delta \text{CO2} = \frac{\delta \text{CO2}_{\text{emitted}}}{1 - g_{V}^{\text{CO2}}} \left[ 1 + \left( \frac{\partial \text{CO2}}{\partial A} \right)_A \left( \frac{\partial f}{\partial T} \right)_{\text{CO2}} \delta T \right]$

CO2 gain $g_{V}^{\text{CO2}} = \left( \frac{\partial \text{CO2}}{\partial V} \right)_A \left( \frac{\partial f}{\partial \text{CO2}} \right)_T < 0$

$\delta T_s = \frac{\Delta_0}{1 - g_{V}^{\text{CO2}} - g_{T}^{\text{CO2}} \delta \text{CO2}_{\text{emitted}}}$

Indirect $T$ gain $g_{T}^{\text{CO2}} = \Delta_0 \left( \frac{\partial \text{CO2}}{\partial V} \right)_A \left( \frac{\partial f}{\partial T} \right)_{\text{CO2}}$

**Some References:**


